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The first demonstration of phase-matching between an electron wave and a light wave

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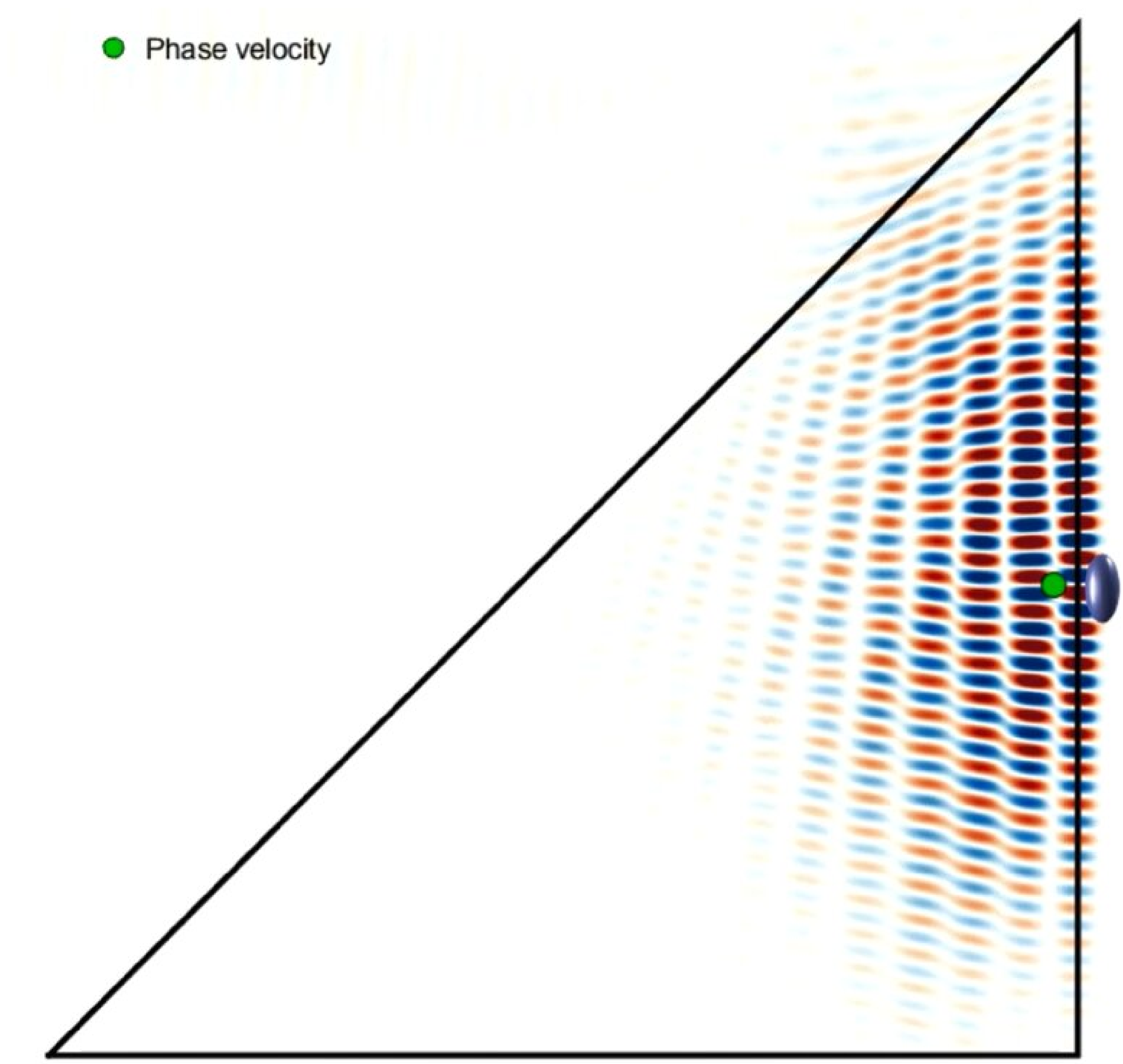


Computer simulation of the electron-light interaction. The laser light (red-blue wave pattern) interacts with the electron wavefunction (elongated sphere) that passes nearby. This unique experimental setup assures that the electron exchanges energy with the laser in a resonant manner – achieving the precise conditions of the Cherenkov effect. Credit: Dahan et al.

While researchers have conducted countless studies exploring the interaction between light waves and bound electron systems, the quantum interactions between free electrons and light have only recently become a topic of interest within the physics community. The observation of free electron-light interactions was facilitated by the discovery of a technique known as photon-induced near-field electron microscopy (PINEM).

Although some experiments using PINEM methods have yielded interesting results, the free-electron light interactions observed so far are fairly weak. This is mainly because PINEM methods gather localized and near-field measurements without addressing the velocity mismatch between free electrons and light, which is known to limit the strength of their interaction.

Researchers at Technion–Israel Institute of Technology have recently observed a strong interaction between free electron waves and light waves, using a hybrid electron microscope they developed. Their observation of coherent electron phase matching, which is also a type of inverse-Cherenkov interaction, demonstrates how the nature of electron wavefunctions can alter electron-light interactions.

"This has been a long journey for me personally, as one could say that I've been pursuing this experiment for 7 years now," Ido Kaminer, one of the researchers who carried out the study, told Phys.org. "I started working on the Cherenkov effect 7 years ago, around the time that I moved to MIT for a postdoc. Already at that time, the Cherenkov effect had 80 years of history since its first observation in 1934 (and a Nobel prize in 1958)."

The Cherenkov effect, named after Pavel Alekseevic Cherenkov, the physicist who first observed it, is a phenomenon that occurs when a particle that carries an electric charge travels through a transparent medium (e.g., water or air), which can lead to the emission of electromagnetic radiation. If the particle is traveling faster than the speed of light in a medium, its passage through the transparent medium causes a brief flash of light, dubbed Cherenkov light.

When Kaminer started studying the Cherenkov effect, back in 2013, it was considered a classical effect; the work of other physicists, including that of Vitaly Ginzburg and Lev Landau, had suggested that quantum mechanics was of no consequence to this phenomenon. The theoretical findings that Kaminer collected over the next few years were therefore intriguing and surprising, as they suggested that the Cherenkov effect actually contains phenomena arising from the quantum nature of charged particles.

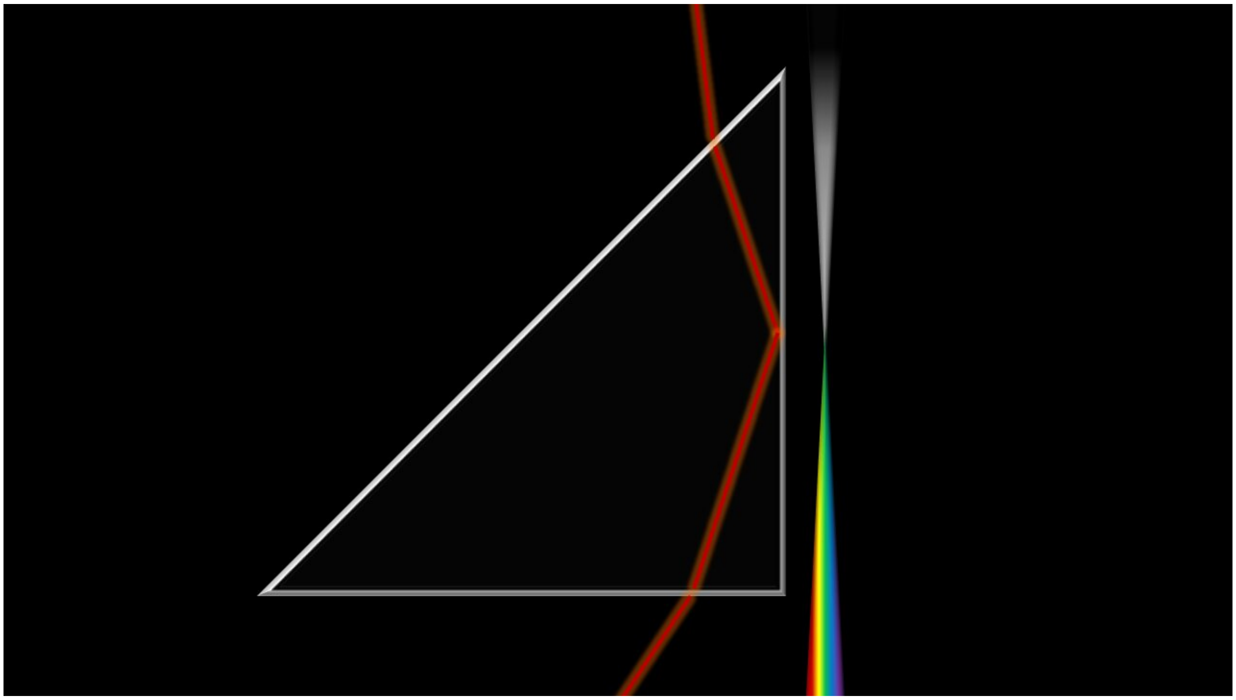


Illustration of the electron-laser interaction that creates the electron energy comb, in which a single electron coherently splits into a wide spectrum of energies, depicted by the rainbow colors. The laser light (red) has to be coupled at a precise angle for the strong interaction to occur, resulting in the electron (illustrated by white light) simultaneously absorbing and emitting hundreds of photons from the laser. As a result, the electron transforms into an energy comb of discrete energies separated by photon energy quanta (illustrated by the rainbow). Credit: Dahan et al.

"My results were quite controversial at the beginning, but over a couple of years, other scientists began to find similar theoretical features in related effects, such as the Smith-Purcell effect," Kaminer said. "These findings increased the general interest in building an experiment to test these theoretical predictions."

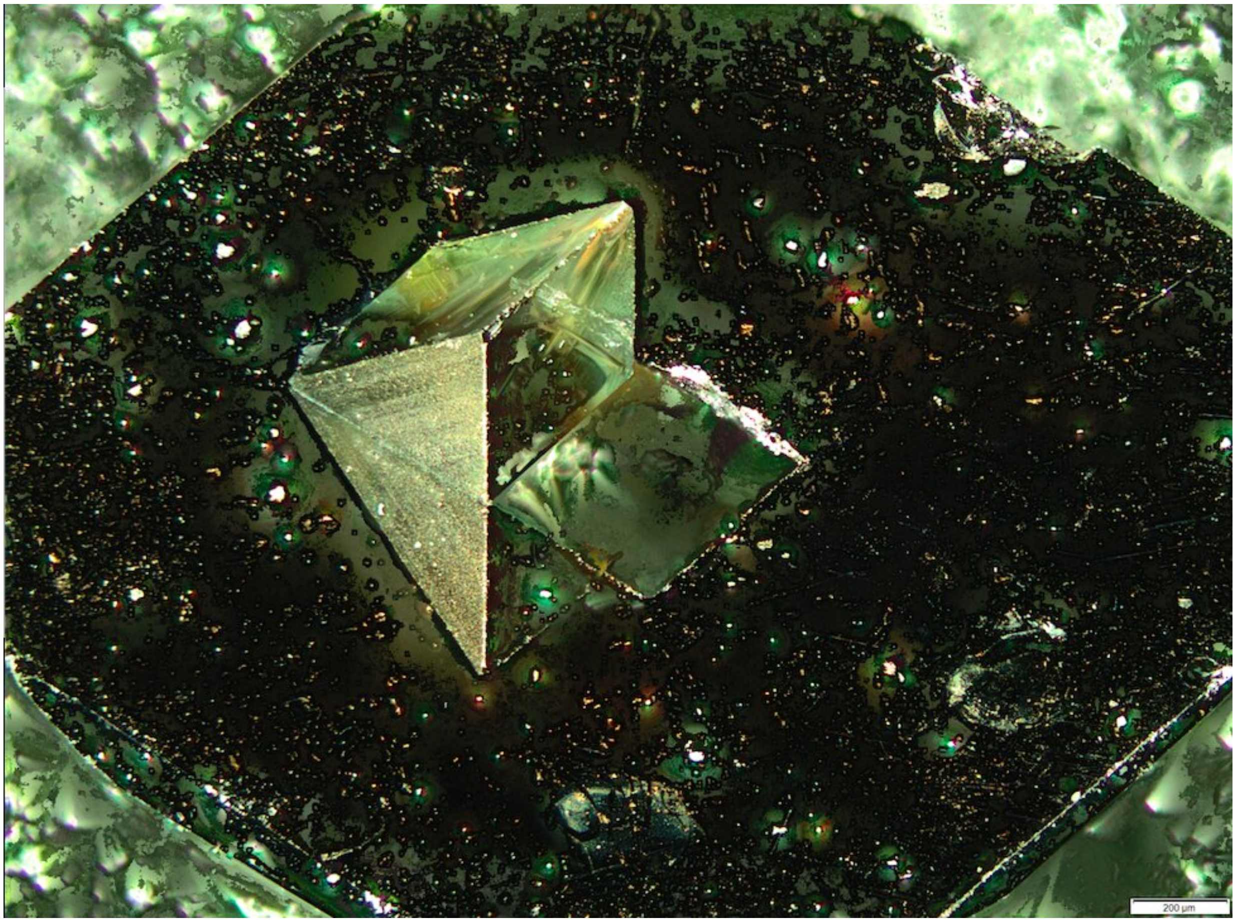
Over the past few years, physicists have delineated three types of quantum phenomena that can theoretically be observed in Cherenkov effect-related experiments. The recent study led by two students who are part Kaminer's lab at Technion, Raphael Dahan and Saar Nehemia, experimentally demonstrates one of these effects for the first time. The other two effects are yet to be confirmed in experiments and remain theoretical predictions.

"I think that it is quite amazing to see the progress that we've made as a community from a historical perspective," Kaminer said. "The experimental setup that we built at Technion for this experiment, which is based on an ultrafast transmission electron microscope, was impossible to imagine in the days of Ginzburg and Landau."

Kaminer and his students conducted their experiments using a hybrid electron microscope that incorporates laser pulses custom-made at Technion. This type of microscope, which is ideal for performing Cherenkov-type experiments, has become increasingly advanced over the past 10 years, especially through the work of Ahmed Zewail and other renowned scientists worldwide.

When an electron is illuminated, its interaction with light waves is typically very weak. The main reason for this is that electrons and light waves move at entirely different velocities (i.e., the electron always moves slower than the speed of light). This velocity mismatch ultimately prevents the interaction between electrons and light from becoming stronger.

In their experiments, Kaminer and his students used a prism (i.e., a transparent object) to slow down the light waves in the proximity of an electron. By precisely matching the angle at which the electron was illuminated, they were able to slow down the velocity of light waves to the point where it matched that of the electron. This match in their velocity produced an effect known as phase matching.



An optical microscope image of the prism that the researchers used in the experiment. This 0.5 mm prism was inserted into our ultrafast transmission electron microscope by first attaching it to a 3 mm surface (darker background) with a square hole (at the center of the image). The prism alignment process was extremely precise to ensure that the electrons passing nearby interact resonantly with the light in the prism. These electrons then pass through the square hole at the center of the surface. Credit: Dahan et al.

"Our approach enabled the observation of a very strong interaction and other coherent quantum behaviors of free electrons that were never seen before," Kaminer explained. "The idea of matching the light velocity and the particle velocity is exactly the Cherenkov effect. In other words, the condition for the strong interaction is the same as the condition necessary for the Cherenkov effect and is also what scientists in other fields call phase matching. The fact that these different concepts can be combined in this way is really beautiful, in my opinion."

The researchers' demonstration of phase matching between an electron wave and a light wave reveals a new type of optical nonlinearity, where relativistic free electrons take on the role of crystalline solids as they interact with light. In addition, the team's experiments led to the creation of a free-electron energy comb; a system that is of great interest for attosecond science research.

Attosecond science is an area of optics that specifically examines processes that occur within a few attoseconds (i.e., 10^{-18} seconds), such as the ionization of electrons from an atom or molecule. So far, most experiments in this field have been conducted using attosecond laser pulses, but the findings gathered by Dahan and Nehemia and other students in Kaminer's lab confirm the viability of also using attosecond electron pulses.

"From a fundamental perspective, our experiment proves that the quantum wave nature of a free electron alters its stimulated radiation," Kaminer said. "This is something that has been debated for many years and is still under intense investigation."

The recent study opens up fascinating new possibilities for the study of the Cherenkov effect from a quantum perspective. In their next studies, the researchers will further investigate the effect they observed, while also examining other fundamental questions that remain unanswered.

For instance, while all previous experiments investigating the Cherenkov effect gathered observations of light waves in three dimensions, theorists have also hypothesized the existence of a two-dimensional Cherenkov effect. In their future research, Kaminer and his colleagues will attempt to observe this unique phenomenon experimentally.

"The quantum nature of light is usually neglected for interactions with free electrons, but the strong interaction we achieved here can hopefully change that," Kaminer said. "Such quantum effects enable important technology too. We started to investigate chip-scale electron accelerators in our setup (called ACHIP, i.e. accelerators on chip). The quantum nature of the electrons raises super interesting questions about such devices and will hopefully help to improve them."

More information: Raphael Dahan et al. Resonant phase-matching between a light wave and a free-electron wavefunction, *Nature Physics* (2020). DOI: 10.1038/s41567-020-01042-w

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